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Design Recommendations for Energy Systems

A UK Energy Community Study

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Abstract— One of the key elements towards a decentralised energy sector is the consumers' choice and participation, as the concept of energy prosumer is gaining more and more ground and energy community projects are spouting across UK. In order for the upcoming energy systems to deliver their potential financial benefits, holistic design needs to be assessed by quantifying the most relevant design aspects (size and operation) and the energy flow through the energy system. Thus, the predominant aim of this study is to provide design recommendations for energy systems suitable to be used in an energy community, which can be expanded to futuristic energy systems. The aspects which were considered include: detailed consumption and generation profiles, charging patterns and limitations that a real energy storage systems of given rated energy and power will impose to energy systems.

Keywords—energy community; energy management; sizing; design recommendations; decentralised systems; battery management.

I. INTRODUCTION

Considerably different scenarios have been predicted considering the form of the energy sector in next few decades. Despite the variety, most of the energy business people agreed that consumers' choice and participation will be one of the substantial key elements towards the new decentralised energy sector [1]. Nowadays, the concept of 'energy prosumer' is gaining more and more ground within the energy market as multiple consumers produce domestically electricity [2] and due to dynamic energy pricing, consumers develop sensitivity to own energy consumption (demand side management). A recent UK study quantified that by 2020, 44% of the UK energy will be generated by prosumers and 1million homes could be supplied with electricity from energy communities [3]. Additionally, the UK government has been encouraging individuals to work as a group, and within the last five years, more than 5,000 energy community led projects have been sprouting across the country, as more than 50% of the citizens expressed their interest of getting involved in energy communities to potentially reduce their electricity cost [4].

For this paper, 'energy community' is defined as a group of neighbouring dwelling homeowners setting up their own renewable installations, and by trading among themselves, the community energy storage (CES) and the power grid, they target, with the help of a local management authority, to the minimum energy cost and maximum revenues. In order for the community prosumers to maximise their incomes, instead of

purchasing the PV excess energy to the grid operator for a low export tariff, they can sell the generated power instantly to a neighbouring property during the peak tariff. This action allows trading renewable energy excess among the community members at preferential cost, mutually convenient for both the sellers and the buyers.

Trading within community members provides high returns to communities with low PV penetration since, if the PV penetration is high, it is very likely that most community members will become net PV energy exporters and being rewarded with a low energy price during day time, whilst during night time, they will have to import electricity during peak prices. A community battery may become an important component in an energy community as it can enable to satisfy night energy consumption from daytime PV energy generation. In addition, overnight charging of the battery during off-peak energy may help to improve the finances in days/seasons with low amount of PV generation. Since the price of the energy storage system is high, sizing it correctly is very important so that the relative financial benefits (revenue vs system cost) are maximised in order for the additional expenditure to become economically viable.

There are four energy activities that the examined community gets involve to: *generate energy* (PV installations at specific community houses), *reduce circulation of power* (by controlling the energy flow), *manage energy* (balancing local supply and demand instantly) and *purchase energy* (collective trading among community members and grid) [5]. Energy communities can potentially unlock opportunities for their members by reducing energy bills, by decreasing carbon emissions and by promoting the local engagement, the energy security, the leadership and the control of the energy flow [3], [4], and [6]. Furthermore, by acting within an energy community, and hence, focus on local equity, participation and control, the unite people can deal better with energy challenges considering their local area, while increasing knowledge, understanding and awareness of energy issues in general [3]. However, to receive fully the potential benefits of energy communities, holistic design needs to be implemented to provide the suitable elements and energy flow for the system.

In this paper, section 2 analyses the examined energy, section 3 explains the examined parameters, section 4 provides the main results and states design recommendations for futuristic energy systems and section 5 summarise conclusions.

II. ANALYSIS OF THE EXAMINED ENERGY COMMUNITY

A. Configuration of the energy community

The overall examined energy system consists of an 8-house neighbourhood, PV installation sized corresponding to the type of the house, a community energy storage system (CES) and the power grid. Real consumption and generation power acquired with one minute time resolution in the Midlands region of UK [7], [8] were used as the imported dataset. All the houses interconnected, and also, this local bus was connected the CES and to the external power grid, as depicted in Fig.1.

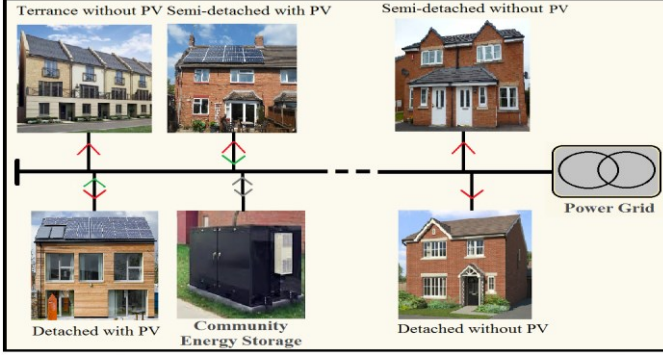


Fig. 1: Configuration of the examined energy community network

Each member of the community can act as prosumer, if the house accommodates a roof PV installation. There are four uses for the generated PV power listed below in a high-to-low return value: (i) it can be consumed internally by the loads of the particular house, (ii) can be sold to other community members (without or with insufficient PV power), (iii) can charge the CES or (iv) it can be exported to the grid. There are however some restrictions: if the battery is fully charged or if the converter power rating does not allow for the whole amount of power to be absorbed, then the excess power is exported to the grid at lower value. Alternatively, if the battery is empty or if the CES cannot provide the requested load power due to limited converter power rating, then the consumption is supplied from the grid at a corresponding higher cost. Furthermore, the battery is able to benefit from the lower off-peak electricity tariff, and it can charge overnight with Economy7 pricing scheme¹. The aforementioned functions of the energy community can be found in Fig.2 and it depicts how power can flow within community. To ensure the functionality of the community, a local management authority is responsible for the proper operation of the project. The authority earns revenue from the difference between the CES charging and the discharging energy price, as the charging energy cost rewarded to the producers less than the discharging energy cost that the consumers will pay. Also, the tariff for CES discharging which takes place during grid peak times is set to be higher than the off-peak charging cost, to allow the management authority to earn revenues by selling off-peak electricity purchased from grid and stored in the CES to the members during peak time but at a lower cost than the peak tariff.

¹ Economy7 pricing scheme is an available UK tariff, for which between 00:00 and 07:00 of each day, the price per kWh is almost 4 times less than for the rest hours during day.

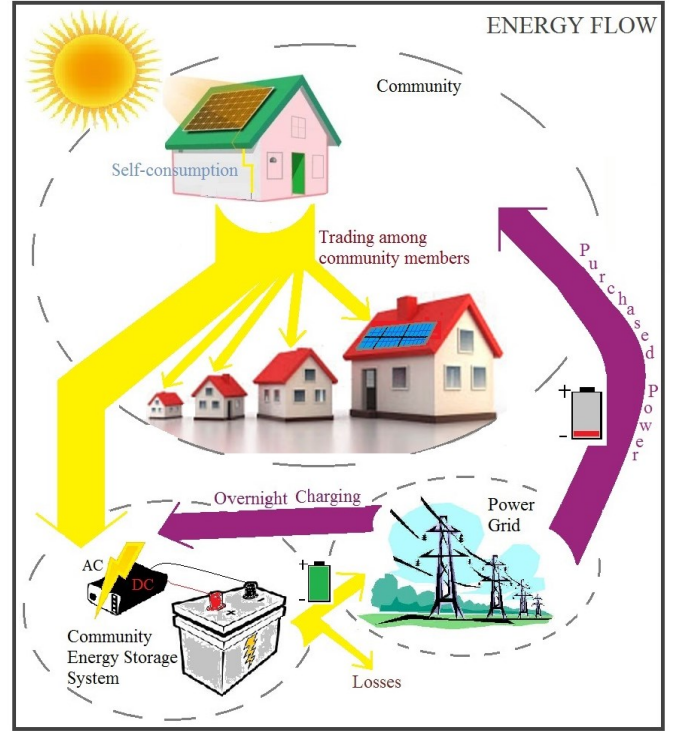


Fig. 2: Power flow within the energy community

Since each energy action (self-consumption, community trading, battery charging and exporting to the grid) provides different financial benefit to the producers, the most financially beneficial action priority for the community members was developed. The following actions are prioritised as highlighted in Fig.3 and these can be further explained as follows:

- 1) *Self-Consumption*: Usage of the generated PV power internally provides the greater benefit for the owners, as they do not need to pay for satisfying their instantaneous load.
- 2) *Community Trading*: The excess PV power that is available after the self-consumption can be sold to the rest of community members to satisfy their immediate consumption at a preferential price. The price for purchasing energy from community members is lower than purchased from either the CES or the grid.
- 3) *Charging the Community Energy Storage*: After the trading among the members, any available excess PV power can charge the CES, as the option of exporting it to grid is the less financially beneficial case.
- 4) *Exporting to the Grid*: If the battery is fully charged or if the power is too high for the rating of the converter which is connected in series with the community battery, then the excess power that cannot be absorbed by the CES is exported to the power grid at the lowest corresponding price.



Fig. 3: Action priority in order to maximize the members' financial benefits

B. Community energy storage model

The community energy storage system was represented by an AC/DC converter interconnected to battery.

1) Battery model:

The battery model used in this paper was the one presented in [5]. The model is described by a detailed Rint electric-circuit, with a variable voltage source and an internal resistance, as shown in Fig.4. After intensive energy analysis of the examined power profiles, it was found that the four battery energy sizes which can represent effectively the results for size variations: 3.3kWh, 39.6kWh, 96kWh and 155kWh.

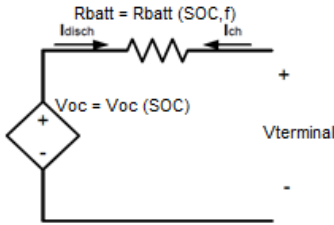


Fig. 4: Equivalent electric-circuit battery model used [5]

2) Converter model:

In order to represent a complete energy storage system, a power electronic converter was considered to connect the battery to the community AC grid. The converter losses were modelled by the same equation as for model 2 in [9] and can be described by (1).

$$P_{\text{converter Losses}} = P_{\text{sb}} + k\% |P_{\text{battery}}| \quad (1)$$

Where

P_{sb} is: the stand-by losses, which accounts for the power consumed by the control platform, the gate drivers, the display, the transducers and the cooling fans and

$k\%$ is: a proportional term with the power processed, which accounts for the processing (semiconductors and filter) losses.

To understand the impact of neglecting the converter losses and the limits that the presence of a converter with a limited power ratings adds to energy systems, comparisons between an ideal converter model (does not include any power losses nor power and current limits) and a realistic converter model with losses and power limits is considered. For the non-ideal converter model, the converter rating was chosen to vary between 5-20kW. The largest power rating was chosen after

investigating the charging and discharging power profiles. For the examined profile, a 20kW converter can operate for the 99% of the required powers. Fig.5 demonstrates the communal battery power profile over one week of winter, for a 67kWh battery considering 75% PV penetration when the converter is ideal and when the power is limited to 5kW converter. The converter limits do not allow powers higher than 5kW (irrespective of direction) to go through the battery, and inevitable will lead to extra energy exports and peak purchased power that will have a negative financial impact.

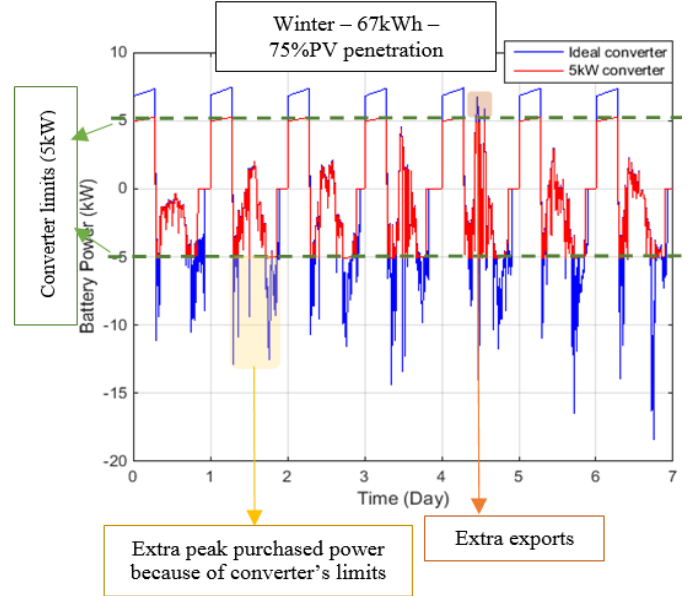


Fig.5: Charging/discharging battery power for ideal and 5kW converter model

III. EXAMINED PARAMETERS

In order to provide design recommendations for the components of energy system, four aspects were chosen to be under investigation. The examined parameters are:

- PV penetration within the community
- Community battery energy size
- Power converter rating
- Overnight charging level

By the term 'PV penetration', this paper is referred to the percentage of community houses with installed PV systems. For each PV penetration, (except the 100% penetration which indicates that all the houses have PVs), the average outcomes of all the possible cases were taken, because as the PV location varies, the generation power changes, as the generation power of each house depends on the house type/size. Also, the battery size can be one of the more complex to be derived and important parameter to be quantified for energy systems. If the battery size is too large for the power load needs, it will not be fully utilised as a daily cycle will not operate. On the other hand, if the battery is too small for the system's power profile, although it will result in low cost for equipment, it will not be able to run for the intended load for as long as it is needed, causing large amounts of PV exports, minimising the off-peak energy to be purchased overnight.

Similar to the battery size, the converter rating needs to be well defined. A low power rated converter may be cheaper but, if the operating circumstances require large power in or out of the CES system, this will be limited to the converter's peak/rated power, leading to PV power exports (low revenues) or grid imports (higher cost). A converter with significantly higher power rating will allow any power level to be provided by the battery but its operational efficiency will be low at reduced loading (<20%) which may occupy most of the operating time and also its installation cost will be high. For these reasons, the converter size needs to be adjusted to the power profile and also, to the battery size, since most batteries will also have a maximum charging and discharging current that result also in additional power limitations.

Fig.6 and 7 illustrate the impact of the converter rating and battery size on the CES charging profiles. More specifically, Fig.6 provides the charging pattern for one winter week, for 100% PV penetration and 155kWh battery size. The state of charge (SOC) of the battery is limited to a 20-70% range to preserve lifetime, and the overnight charging control algorithm chosen for this snapshot aims to perform a full charge. So, the battery should be charging for the 7 hours overnight (because of the off-peak electricity of Economy7) till it reaches the 70%SOC, and then it charges again during daytime but only partly from the limited PV generation available during winter. However, for the red curve, which represents the case of using a relatively small converter compared to the large battery size, the overnight charging cannot reach the 70%SOC, because of the lower charging power and current limits which the converter rating introduces into the system. On the other hand, Fig.7 shows a different situation with low (25%) PV penetration and a smaller (67kWh) communal battery size. The battery is not fully utilised when 5kW converter is used, as the power and current limits do not allow the full overnight charge to take place

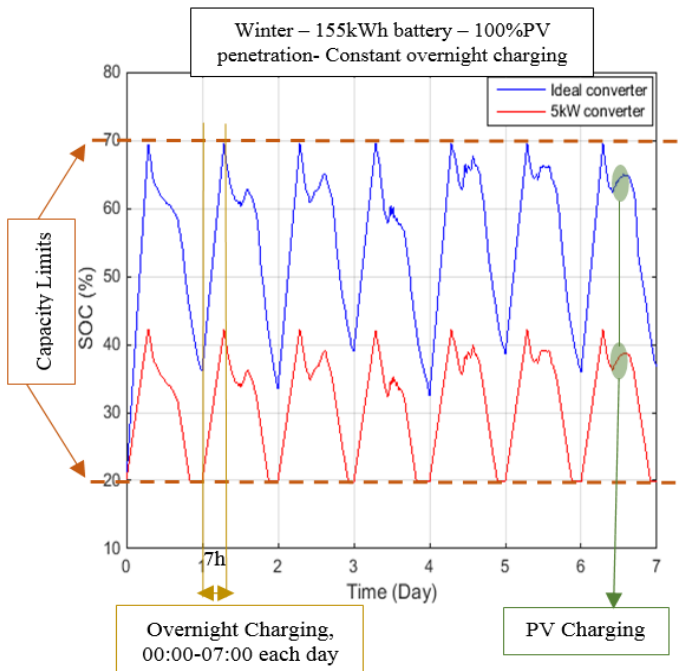


Fig.6: Charging pattern for large battery capacity and small converter rating

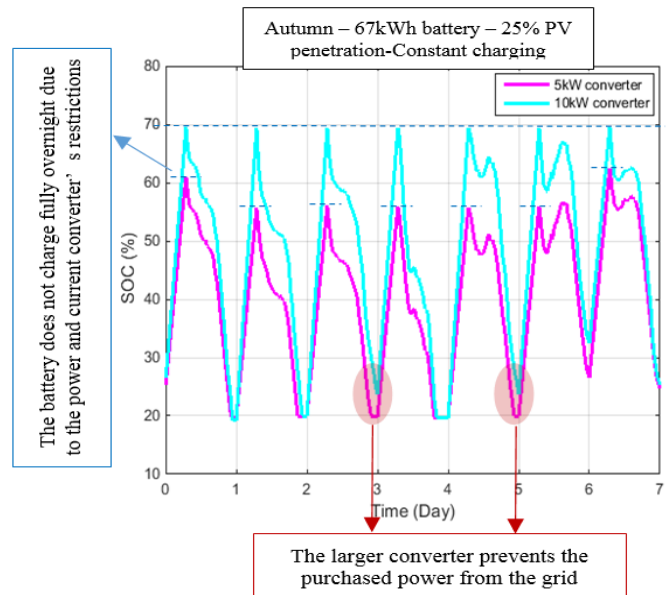


Fig.7: Charging patterns for two different converter ratings (5kW and 10kW)

Lastly, the overnight charging level can change significantly the financial outcomes, as if the battery is not sufficiently charged during off-peak time and the day ahead is cloudy, it will probably be fully discharged before the end of the peak period and hence, electricity will need to be purchased from the grid. On the other hand, if the overnight charge level is too high, any excess PV energy must be exported back to the grid. To solve this problem, in addition to the constant fully charged overnight control algorithm, a more intelligent algorithm (the 'one day before adjusted control algorithm' described in [9]) was used which is expected to minimise the effects of the overnight charging setting and PV penetration in the CES utilisation efficacy. Fig.8 illustrates the charging pattern differences for the intelligent control algorithm when different PV penetration percentages are considered.

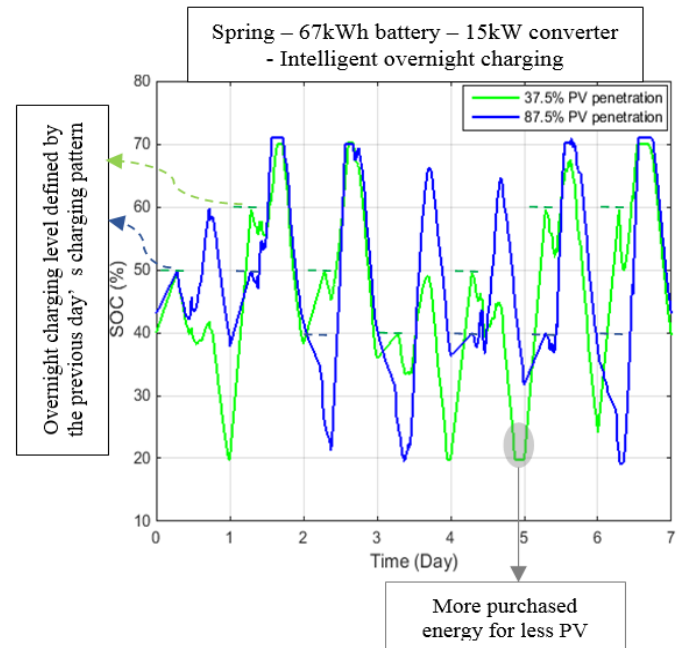


Fig.8: Charging pattern for different PV penetration (intelligent control)

IV. RESULTS AND DISCUSSION

A. Impact of the examined parameters on the outcomes

In the previous section it was shown that each of the 4 examined parameters can affect significantly the charging pattern of the CES and also, it was highlighted that they are correlated with each other. In this section, the impact of the examined parameters on the outcome quantities and hence, on the financial analysis will be investigated. The outcome considered aspects is shown over a sum of 4 weeks - 1 week of each season. The *average electricity cost* which is the average bill for community members is shown in Fig.9 and the *incomes for the management authority* in Fig.10. The *exports* account for the exports to the grid, either because of full battery or restricted rating of converter (Fig.11). The aforementioned figures consist of 4 figures, one of each examined CES size for different converter ratings and PV penetrations.

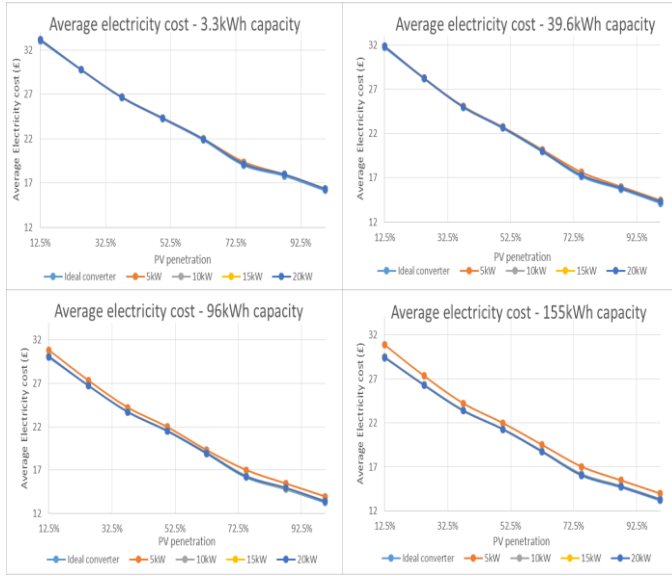


Fig.9: Average electricity cost for different PV %, battery and converter size

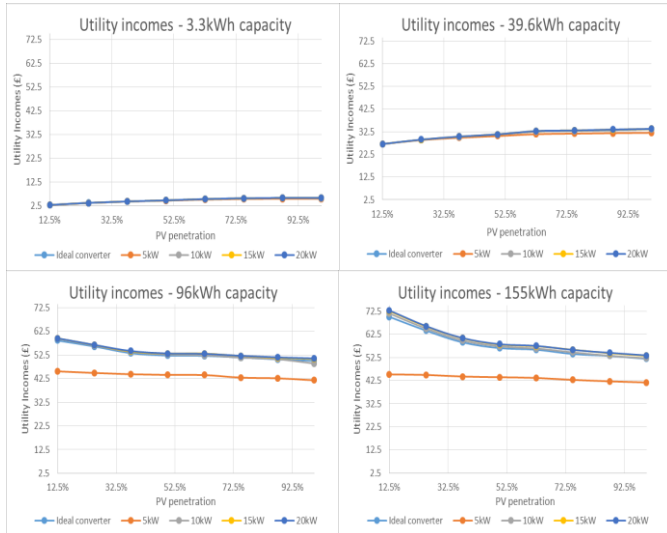


Fig.10: Incomes for the authority for different PV %, battery and converter size

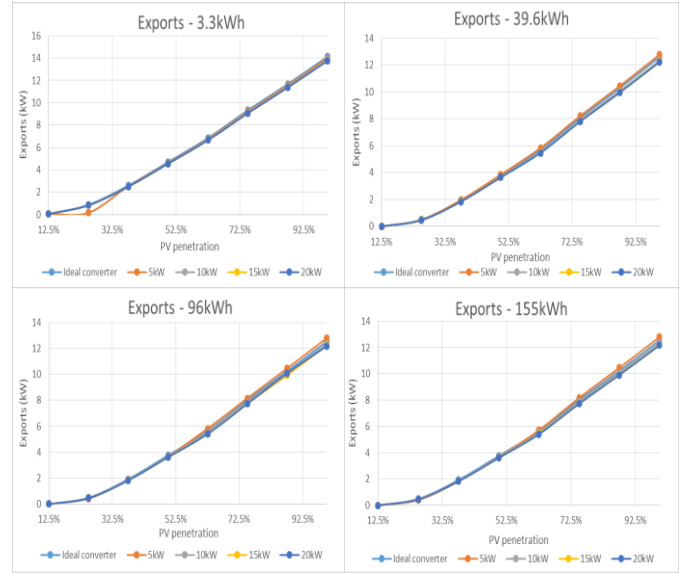


Fig.11: Exports for community for different PV %, battery and converter size

Some of the significant observations/conclusions from Fig.9-11 can summarised as follows:

- From Fig.9 it can observed that the electricity cost for the average community member decreases with the increase of the PV penetration. This is a logical trend since higher PV penetration means cheaper PV energy becomes available to community members without PV installations and with the present of CES, influencing the economy of the community also during evenings. However, the slope of the curve decreases with the increase of smaller PV penetrations which means that above a given PV penetration (72.5%), the average PV generation covers the community consumption resulting in significant PV energy exports.

- The revenues for either the community members (Fig.9) or for the management authority (Fig.10) do not improve significantly after the increase of converter size above a 10kW rating. More specifically, for small battery sizes, an increase of the converter size does not impact the results, but for large battery capacities, the increase of converter rating from 5kW to 10kW can provide up to 40% increase of earnings, whereas a further increase in converter rating from 10kW to 15kW can provide a maximum increase of only a 3% of financial benefits.

- From Fig.10 it is clear that for the 2 smaller battery sizes, the incomes for the authority increase with the increase of the PV penetration. But, for the 2 larger battery sizes, the opposite happens, as the incomes decrease with the increase of the PV penetration. The reason for this is that the large battery used in combination with the high PV generation and the fully charging constant control algorithm; the battery is not fully utilised for this combination. This is because for the control algorithm used, the large battery does not have enough time to get significantly discharged during daytime and cannot capture all the available PV excess power. Thus, too much overnight charging blocks the possibility to store the generated PV power and hence, the excess PV power will be exported to grid at considerable lower tariff.

B. Design recommendations

After extensive analysis of the observations regarding the relationships between the examined parameters and the outcomes, design recommendations were extracted for a generic energy system.

Recommendation 1:

The increase of the PV penetration will provide increase of holders' revenues. However, after a certain critical PV percentage and hence, after a threshold level of generated energy, the financial benefits from the investment decrease to a point where a further increase of the PV penetration will not lead to any significant financial benefits for the holders. This is happening for all energy systems, without and with energy storage. For the former case, an increase of the PV generation above the community consumed power will not provide any great financial benefit, as the excess power will have to be exported to the grid providing low revenues. For the latter case, if the generation increases above the community instantaneous consumption, the excess energy will be stored in the ES for later use. If the battery is relatively small for the community power profile, then it will not be able to store all the available excess energy, and hence, a significant proportion will be exported. Alternatively, if the battery is suitably sized for the corresponding power profile, it needs to utilise the overnight charging. Without overnight charging, the PV penetration needs to be adjusted to the battery size and to the percentage of the consumed energy which needed to be satisfied from the PV generation. On the other hand, if the battery is large enough and charges fully overnight, then the consumption will be satisfied from the overnight charged energy, and so, most of the PV generation will be exported to the grid, because during the following morning the battery will not be sufficiently discharged to store the overall excess PV generated power. For intelligent overnight control algorithm, the available battery charging capability can be adjusted to accommodate fully the next day PV generation, maximising the PV energy usage and minimising the imports (zero peak and minimum off-peak). Fig. 12 demonstrates the flow diagram which provides guidance for PV penetration sizing of the energy system.

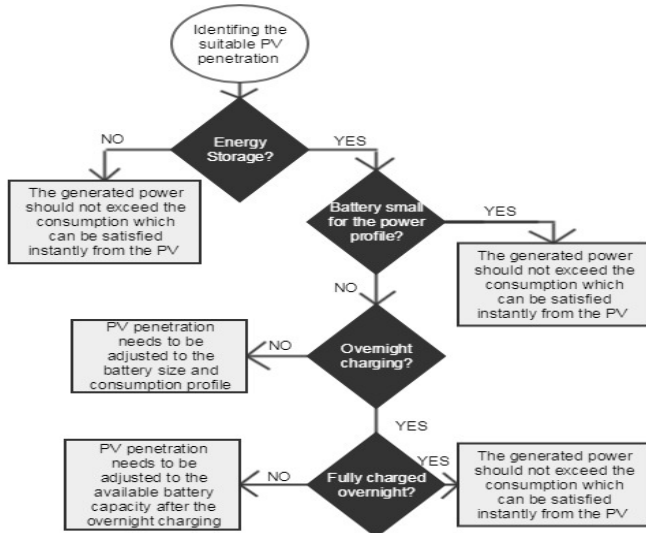


Fig.12: Flow diagram for PV penetration sizing of energy systems

Recommendation 2:

A converter introduces power and current limits into the energy system, as the power going through the energy storage needs to be adjusted to the converter power rating. Also, a converter adds extra power losses to the system (when it operates). Fig. 13 quantifies the operational cost of the converter for the examined energy community for the 4 examined battery sizes over one year period. The converter cost was found by comparing the case of the ideal converter and the non-ideal ones. The converter's operational cost is due to the extra exports and purchased power which results because of the converter rating limits and converter losses. In addition, from the same figure, it can be verified that the most suitable PV penetration for the examined energy system is the 72.5%, as above this level, the converter cost has a local maximum.

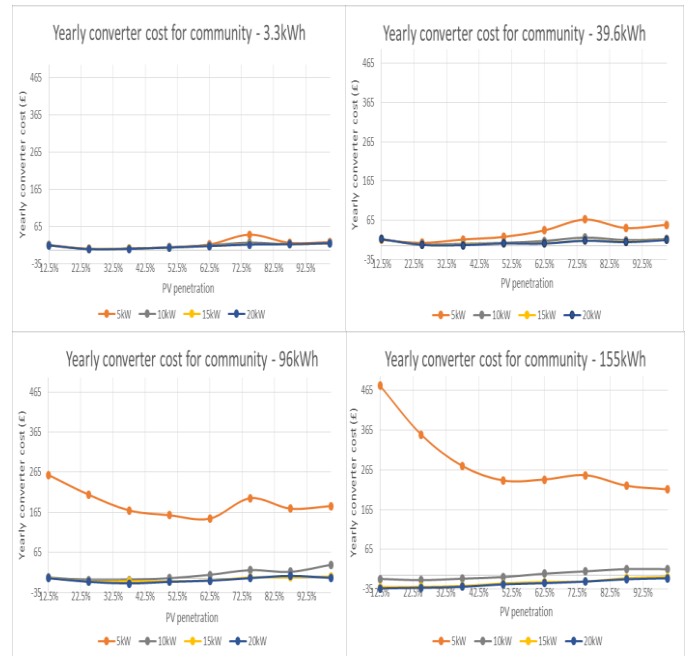


Fig.13: Yearly converter's operating cost for community for the 4 battery sizes

Additionally, from Fig.9-11 and 13, it can be overall concluded that above a certain converter size, the increase of the financial benefits and the reduction of exports and converter operational cost is not significant. For this specific energy system, an increase of the power converter rating above 10kW does not lead to any significant improvements of the examined outcomes. The justification for this comes from the power profile analysis; for all PV penetrations, the duration of the power which needs to charge or discharge the battery (the power excess remaining after the self-consumption and the trading among the community members), which does not exceed 10hours over one year for powers higher than 10kW.

All in all, in order to size the power converter suitably on the power profile, the power frequency needs to be considered. If the peak powers are occurring for very short periods through the year, sizing the power converter according to the maximum power, is not financially beneficial, as smaller converters could provide the same benefits with lower installation cost and lower losses due to higher efficiency at a given power loading.

Recommendation 3:

As it was stated in previous sections, the level of the overnight charging is very important for the consumers' finances and for the revenues of the management authority which supervise the project. In order to identify the usefulness of the control algorithm which is used to charge the battery overnight, the battery size needs to be considered. For small battery sizes for the corresponding power profile, the battery needs to be fully charged overnight, as its energy capacity is not sufficient enough to cover the load needs. On the other hand, if the battery is very large for the consumption needs, and also, if it charges fully during the off-peak electricity tariff, then the generated PV power could not be stored in the battery, as there will be not enough available energy charging range defined only by the energy consumed during the morning. Thus, instead of fully charging the battery overnight and so, forcing exports of the generated PV power, a more intelligent charging method needs to be developed for large battery capacities and high PV penetration/generated PV energy.

Fig.14 shows the yearly financial benefits for having the proposed intelligent control algorithm against the fully charged overnight. The negative values illustrate a usefulness of the constant overnight charging control algorithm over the intelligent one; this is the case for small battery (3.3kWh and 39.6kWh capacities) and for small power converter ratings (5kW). Therefore, an intelligent control algorithm makes sense only for large battery sizes and PV penetration. In conclusion, the battery of the energy systems should not be fully charging overnight if its size is large for the corresponding power profile and an intelligent control algorithm needs to be used to provide it with most suitable charging patterns.

Recommendation 4:

From Fig.6, 7 and 13 it was concluded that the battery capacity is strongly correlated to the converter rating and hence, in order to size correctly these two components, the combination of both components needs to be considered. To fully utilise the capacity of the battery and the converter size, the converter rating needs to be adjusted to the battery size. In more detail, if the battery is too large for the converter, the battery is not fully utilised (as in Fig.6 and 7), especially during the overnight charging, where the battery could not be fully charged because of the converter limits. On the other hand, if the battery is too small and the converter too big, the converter will not be fully utilised, as it will not reach its rated power and the battery will rapidly be fully charged. Consequently, in order to utilise fully the battery capacity and the converter rating, the inequality (2) which interrelates these parameters during the overnight charging needs to be followed.

$$P_{\text{converter}}(W) \geq \frac{V_{\text{bat}}(V) * C(\text{Ah}) * \text{SOC}_{\text{charging}}(\%)}{\text{overnight_duration}(h) * 100\%} \quad (2)$$

Where

$P_{\text{converter}}$: the power converter rating / converter peak power

V_{bat} : the battery voltage

C : the nominal battery capacity in Ah

$\text{SOC}_{\text{charging}}$: the available SOC range for charging overnight

$\text{overnight_duration}$: the overnight charging duration in hours

V. CONCLUSIONS

One of the key points towards the future decentralised energy sector is the consumers' choice and participation, as the concept of energy prosumer is gaining more and more ground in the development markets and energy community projects are spouting across UK. In order to deliver their promised financial benefits, holistic design needs to be implemented to quantify the suitable element size and operation and the energy flow across the energy system.

In this study, an energy community is investigated, and by identifying the optimal energy flow and the action priority which maximises the financial benefits of the end-users and the local management authority which supervises the project, the impact of the system's parameters was examined. More specifically, it was examined the impact of the communal battery capacity, of the power converter rating, of the PV penetration within the community and of the overnight charging level on the electricity bill of the community members and on the authority's revenues.

Lastly, by observing the response of the aforementioned parameters on the charging pattern of the community energy storage system and how the energy flows within the individuals, the battery and the power grid, design recommendations were provided for generic energy systems, regarding the battery capacity, the converter rating, the PV penetration percentage and the overnight charging control algorithm.

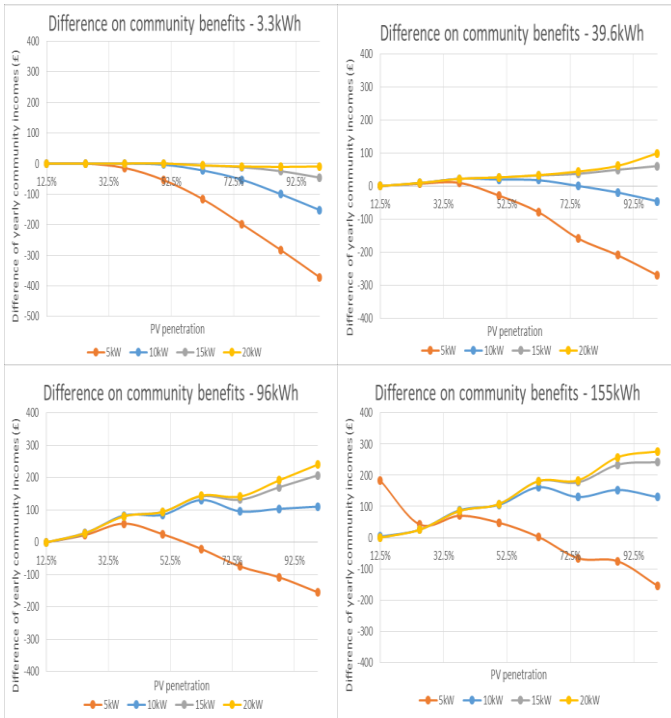


Fig.14: Difference of yearly community incomes for constant and intelligent control algorithms for different battery capacities, converter sizes and PV (%)

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